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Concentration measurement in bubbly liquids - a matter of times

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Abstract

Leaky Lamb waves in an acoustic cavity can be utilized for the measurement of temperature, density and sound velocity of an enclosed liquid. If the sensitivity of these variables to a change of predefined components in a liquid mixture is high enough, an online concentration measurement can be utilized as well. Gas bubbles can influence the measurable times-of-flight which can be disadvantageous for the concentration measurement. This paper will show how simultaneous group and phase velocity measurements can be used to calculate the sound velocity and the concentration in pure liquids, even if gas bubbles are interspersed.

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1. Sound velocity in bubbly liquids - the linearized Orris-Model

The starting point for research into the acoustic properties of bubbly liquids was in the late 1940's. And as the first formula for the sound velocity in a gas-liquid mixture were functions of bulk density and compressibility (e.g. Wood's equation), the measurable sound velocity should be somewhere in between the numerical values of the components (e.g. 340 m/s for air and 1500 m/s for water). This could also be proved experimentally when the sound frequency was far below bubble resonance frequencies and there was almost no bubble interaction. If the operation frequency is increased, the output may be different: An acoustic wave can excite bubbles, these can oscillate, store and release acoustic energy - as a result the frequency dependent phase and group delays of signals are modified. Lamarre and Leville (1995) analyzed bubbly water near the ocean surface, and they explained the measured 'sound-speed anomalies', even higher velocities than in pure water, with a phenomenological dispersion model and with respect to their time-of-flight measurement method. The first physical dispersion model for bubbly liquids was developed by Commander and Prosperetti (1989), taking thermodynamics (see Kieffer (1977)), bubble dynamics, scattering and bubble interaction into account. They also proved their model with some measurements, showing that the phase velocity in a bubbly liquid can be both, lower and higher than in a pure liquid. The effect depends on the operation frequency and is highly associated with the measurable amplitudes. Finally it was to Orris et al. (2007) to include causality to the dispersion equation.

We started with the most comprehensive dispersion equation of Orris et al. to find a simplified model that is suited for integration in a measurement device. The conditions are high angular frequency ω (i.e. large radius a of

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monodispersed gas bubbles in comparison to the acoustic wavelength) and a low volume fraction V of gas in the liquid. Therewith, it is possible to find phase and group velocities c_{ph}, c_{gr} if c_0 is the sound velocity of the non-dispersed liquid, see Rautenberg and Münch (2015):

$$c_{ph}(\omega) = c_0 \cdot \left(1 + \frac{3}{2} c_0^2 \frac{V}{\omega^2 a^2}\right), \qquad c_{gr}(\omega) = c_0 \cdot \left(1 - \frac{3}{2} c_0^2 \frac{V}{\omega^2 a^2}\right) \qquad \Rightarrow \qquad c_0 = \frac{1}{2} \cdot \left(c_{ph} + c_{gr}\right) \tag{1}$$

The sound velocity of the pure liquid is the arithmetic mean value of phase and group velocity, but we could also find a limit for this approximation. The idea was to look at the relative span K between phase and group velocity, that is characterized by a critical volume fraction V_{crit} and is reverse proportional to the square root of the pure liquid's sound velocity. Considering the deviation between averaged sound velocity and true value, a maximum deviation of 0.1 m/s can be reached with $\tilde{K} \approx 0.283$ (Rautenberg and Münch (2015)):

$$K = \frac{c_{ph} - c_{gr}}{c_{ph} + c_{gr}} < \frac{3}{2} c_0^2 \frac{V_{crit}}{\omega^2 a^2} \approx \frac{3}{2} \cdot \tilde{K} \cdot \frac{1}{\sqrt{c_0}} \tag{2}$$

As the dispersion effect of eq. (1) and (2) could have been already proved in laboratory experiments, the aim of this contribution is to find a robust software implementation and to prove it in harsh industrial test benches.

2. Time-of-flight measurements

The phase delay τ_{ph} is defined as the ratio of the signals phase ϕ and angular frequency ω in the frequency domain. The group delay τ_{gr} is defined as the phase derivative with respect to angular frequency:

$$\tau_{ph}(\omega) = -\frac{\phi(\omega)}{\omega}, \qquad \tau_{gr}(\omega) = -\frac{d\phi(\omega)}{d\omega} \tag{3}$$

To keep the computational effort low, it is desirable to approximate the group delay with only one value, that is calculated in the time domain, e.g. the position of the maximum of the signal burst's envelope function. This implies that the slope of the phase is almost constant in the frequency band of interest, which is characteristic for linear phase systems. As the measurement system (here an acoustic waveguide sensor LiquidSens Probe, see Rautenberg et al. (2014)) is not necessarily linear in phase we use digital all-pass filters for linearization, see Fig. 1. The phase delays are almost equally spaced whereas the group delay is almost constant for all equally spaced frequencies. The remaining low frequency fluctuations are due to flow effects in the measurement setup. Apart from that, the group

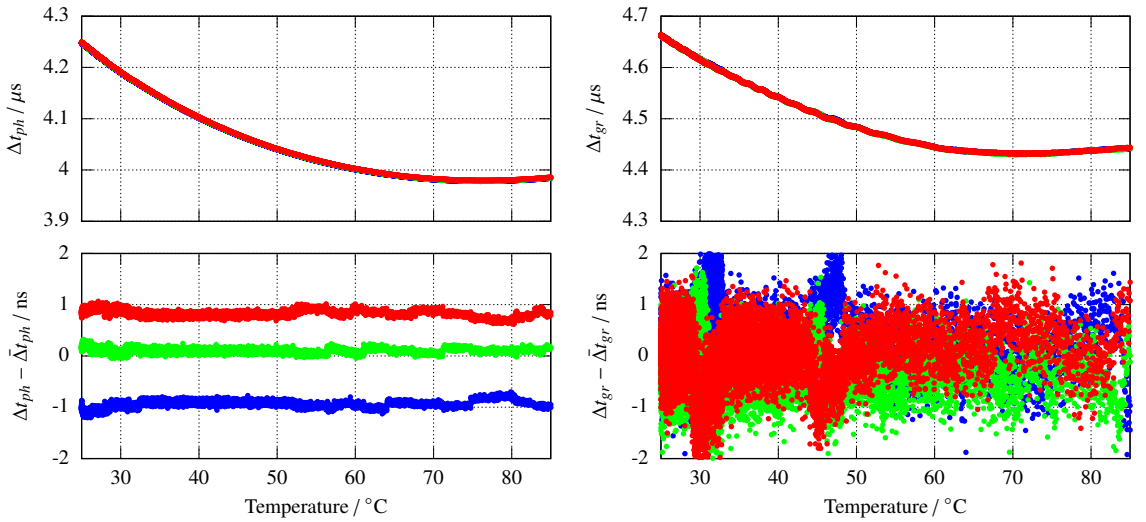

Fig. 1. Phase delay Δt_{ph} and group delay Δt_{gr} in non-dispersed water as a function of temperature (top) and their deviations (bottom) for three different frequencies f_1 (blue) < f_2 (green) < f_3 (red)

delay is about one magnitude order more fluctuating than the phase delay. This is due to the fact that, in a noisy signal, the flat maximum of the envelope function is less stable than a phase criterion, e.g. the zero crossings. Nevertheless, there are model based approaches to overcome these limits, e.g. in Carlson et al. (2003).

3. Measurement and results

As the implemented algorithms for time-of-flight calculations were satisfactory with the LiquidSens system, the prototypic setup was put under test in harsh industrial environments.

The first test bench is an industrial cooling lubricant conditioning system. Fig. 2 shows sound velocities as well as the determined concentration values for a whole week. Gas bubble insertion causes the sound velocities to shift in opposite directions. It is obvious that a sole phase velocity measurement will cause a system to fail because the sensitivity of sound velocity to a change of quiescent liquid properties is much smaller than the cross sensitivity to dispersed gas bubbles. Moreover, the very slow degassing process can even be misinterpreted as a concentration change if for instance statistical moments are used to identify 'process noise'. However, the combined measurement of both, phase and group velocity, gives much better results. Moreover, the masking of valid values, following eq.(2), gives satisfactory concentration values for most of the time. The new values, especially K of eq.(2), can also be used to optimize the integration of the measurement system into the process. For instance, it is sometimes possible to modify the position of the measurement system in the tank. Fig. 3 (left) shows the results of concentration measurement for two different positions in the already mentioned conditioning system. The availability could be increased from initially 71.2% to 92.6% with the same measurement setup.

The second test is a LiquidSens Liner (DN25) within a pipe system and streaming water ($\bar{v}$ <1.5 m/s) at slightly varying room temperature. The new criteria are well suited to compensate the influence even in streaming liquid, see Fig. 3 (right). As the sound velocity is an important parameter in the calculation of volume flow in ultrasonic flowmeters, there is only little volume fraction of gas allowed in such systems. With the presented new sound velocity measurement, the gas bubble influence can be compensated and higher gas volume fractions may be tolerable.

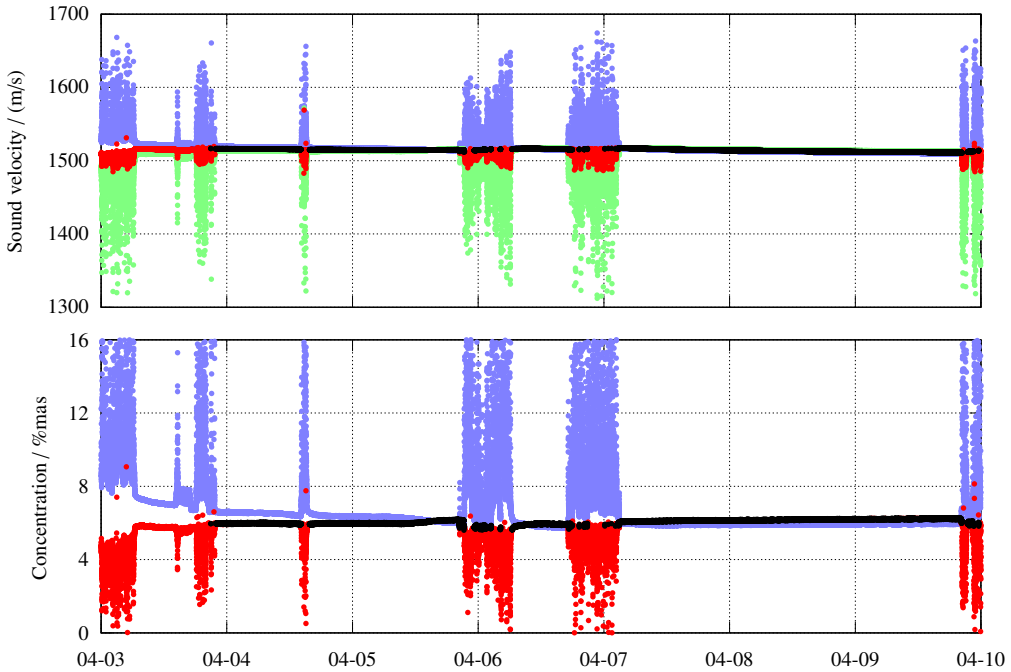

Fig. 2. Sound velocities (top) and concentration values (bottom) over time for an entire week in April 2015, calculated with different signal criteria: phase delay (blue), group delay (green), averaged values(black and red) - the invalid values (red) are identified with eq.(2).

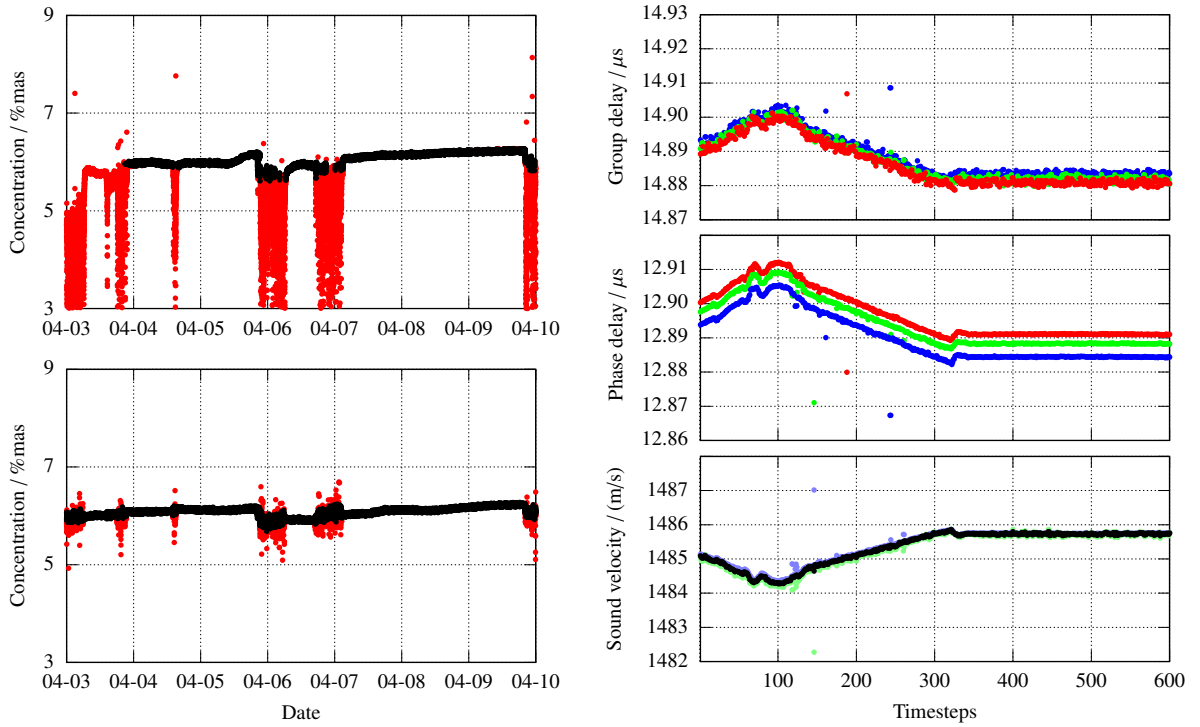

Fig. 3. (left) Concentration measurement of the same liquid but at different positions and (right) group and phase delays (f_1 (blue) < f_2 (green) < f_3 (red)) as well as sound velocities in streaming water (DN25) as a function of time. The averaged sound velocity (black) shows almost no bubble influence.

4. Conclusion

It has been shown how simultaneous group and phase velocity measurements can be used to calculate the sound velocity of the pure liquid, even if gas bubbles are interspersed. Apart from that a new criterion to evaluate the gas bubble influence has been introduced and tested in harsh industrial environments. Therewith the availability of measurement values could be increased to a great extent. It could also be demonstrated that the new method will be advantageous for ultrasonic flow measurement devices. But the technological basis for this robust sound velocity measurement is the acoustic waveguide, realized for instance in the LiquidSens systems. It is due to the large aperture of the emitted Leaky wave, that parts of the sound wave reach the receiver, even if the liquid is interspersed with gas bubbles - a mandatory condition for acoustic measurements at all.

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